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14. ABSTRACT
The study of wall turbulence dates back more than a century. Recently, however, a number of studies suggest that the flow in the inner region (i.e., the viscous sublayer and buffer layer) is not "universal"—and actually depends upon the specific type of wall turbulence. Many of these new insights on wall turbulence are recent because we have only recently developed the experimental techniques, such as volumetric particle-image velocimetry, to fully resolve wall turbulent flows. The objective of the study described here was to determine whether an even more

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Report Title

Final Report: Evanescent-Wave Visualizations of the Viscous Sublayer in Turbulent Channel Flow

ABSTRACT

The study of wall turbulence dates back more than a century. Recently, however, a number of studies suggest that the flow in the inner region (i.e., the viscous sublayer and buffer layer) is not “universal”—and actually depends upon the specific type of wall turbulence. Many of these new insights on wall turbulence are recent because we have only recently developed the experimental techniques, such as volumetric particle-image velocimetry, to fully resolve wall turbulent flows. The objective of the study described here was to determine whether an even more recent technique, evanescent-wave particle tracking velocimetry (PTV), could be used to visualize a plane (with dimensions exceeding 100 wall units) of the viscous sublayer parallel to the wall in fully-developed turbulent channel flow. Although the start of this study was delayed by visa issues, we have, after six months of work, demonstrated that the initial version of our evanescent-wave illumination and imaging system can obtain high-quality images of the tracer particles with a temporal and spatial resolution suitable for wall turbulence that are suitable for PTV analysis, using only 30% of the available laser power.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

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TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Vladimer Tsiklashvili	1.00
FTE Equivalent:	**1.00**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Minami Yoda	0.00	No
FTE Equivalent:	**0.00**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

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Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Technology Transfer

FINAL PROGRESS REPORT

Evanescent-Wave Visualizations of the Viscous Sublayer in Turbulent Channel Flow

Proposal number 66195EGII

PI: Minami Yoda, *Georgia Institute of Technology*

Problem Statement

Understanding the characteristics of wall(-bounded) turbulence—the thin flow region next to the wall where viscous effects dominate—is the key to understanding the drag and lift forces acting upon solid surfaces moving through air or water, such as aircraft wings, helicopter blades, and ship hulls. Yet recent studies suggest that the flow in the inner region (*i.e.*, the viscous sublayer and buffer layer) actually depends upon the specific type of wall turbulence, calling into question the classic "universal" scaling of wall turbulence.

This brief final report summarizes the results from a feasibility study (supported by a Short-Term Innovative Research grant) with the objective to evaluate whether evanescent wave-based particle-tracking velocimetry (PTV) can be used to visualize a "slice" of the viscous sublayer parallel to (and within ~1.5 wall units of) the wall in wall turbulence. The specific type of wall turbulence that was visualized here was fully-developed turbulent channel flow through a 1 mm square "minichannel" where a wall unit ≈ 1 μm at a spatial resolution, based on the particle diameter, of 0.5 wall units.

Feasibility was an issue because of the sizable challenges in extending evanescent-wave PTV to flows with speeds of O(1 m/s), or three orders of magnitude greater than the microchannel flows previously studied with this technique. Perhaps the greatest challenge was ensuring that there was enough light scattered by the tracers (and enough tracers this near the wall) in this high-speed flow to image the tracer particles with high signal-to-noise ratio (SNR), especially tracers with an average radius $a \le 0.25$ μm (based on a wall unit of 1 μm).

For the turbulent channel flow water, seeded with fluorescent $a = 0.25$ μm polystyrene (PS) particles (Life Technologies F8812 with excitation and emission peaks at wavelengths λ = 580 nm and 605 nm, respectively) at volume fractions $\phi \approx 60$ ppm was driven at average speeds $\bar{V} \le 1.75$ m/s by a chemical metering pump (Stenner 85mjh7a1stg1) through a test section consisting of a 1 mm square groove machined in an aluminum plate of length 7 cm (Fig. 1) and sealed using a gasket with a 1.5 mm thick glass window. The channel was illuminated by evanescent waves created by the total internal reflection (TIR) at the glass-water interface of the coincident beams at a wavelength λ = 532 nm from two diode-pumped solid-state lasers* (DPSSL) (Spectra-

Figure 1 Sketch of the 1 mm × 1 mm groove machined in the aluminum plate.

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* Purchased using a DURIP award (Imaging System for Extending Evanescent-Wave Particle Velocimetry to Wall Turbulence, proposal number 61493-EG-RIP).

Physics Explorer 532-2Y) (Fig. 2). The fluorescence from the particles illuminated by the evanescent wave, which has an estimated intensity-based penetration depth z_p (*i.e.*, the distance from the wall where the intensity of the illumination is reduced by a factor of e) of 100 nm, are imaged by a high-speed 1024 × 1024 pixels intensified CCD (ICCD) camera* (Princeton Instrument PI-MAX4) with a magnification 40, numerical aperture 0.55 microscope objective (Leica 506059) using a longpass (wavelength) filter that only transmitted the red-shifted fluorescence (*vs.* the laser illumination at λ = 532 nm).

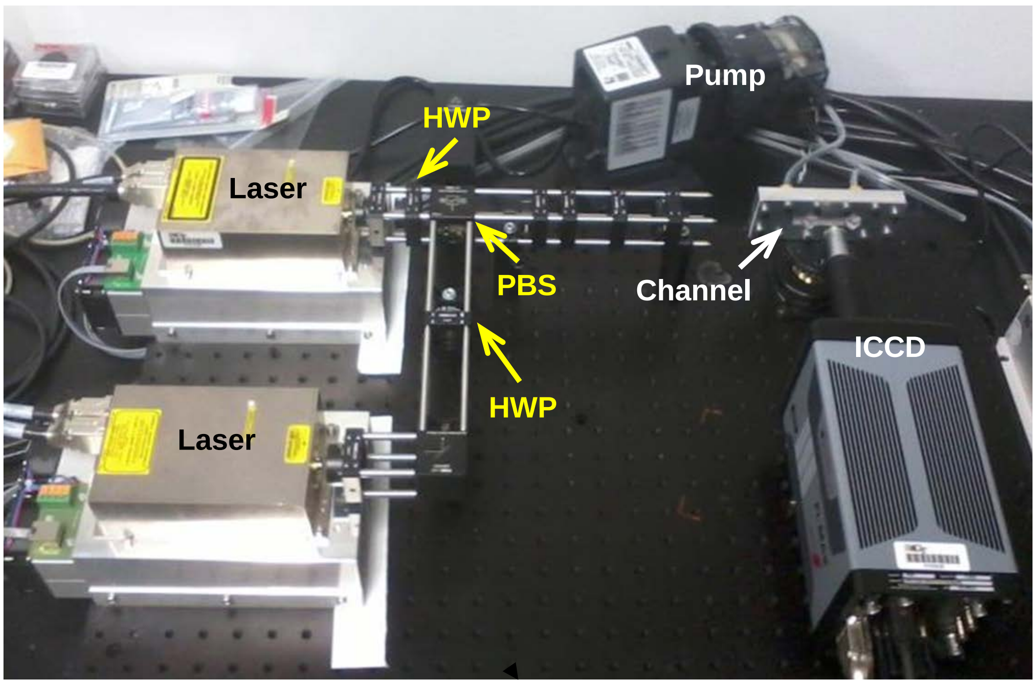

Figure 2 Picture of the experimental setup showing the two DPSS lasers on the left, the ICCD camera on the lower right, and the minichannel and pump on the upper right. Here, HWP and PBS refer to the optical components for combining the two laser beams, as defined in the text.

Figure 3 Top view of the 1 mm square channel showing the multiple spots along the channel axis illuminated by evanescent waves (due to TIR at the glass-water interface) and the prisms that couple the beams from the two DPSSLs into the channel on the left and out of the channel on the right.

The beams are coupled into and out of the glass window, with several successive TIRs along the length of the channel, using a pair of isosceles right-triangle prisms (Fig. 3). The linearly polarized beams from the lasers are combined using half-wave plates (HWP) to rotate their polarization by 90° and a polarizing beamsplitter cube (PBS) that transmits one linear polarization, and reflects the other polarization by 90° (Fig. 2).

In evanescent-wave PTV, the two velocity components parallel to the wall are determined from the displacement of individual tracer particles in two successive exposures of the particles (illuminated by evanescent waves) separated by a known time interval Δt. Given that the velocity scales are O(1 m/s) and the field of view of the entire image is O(0.1 mm), the time interval within the image pair must be very small, with $\Delta t = O(1\ \mu s)$. Obtaining an image pair with such a small temporal spacing requires using a pair of lasers and a "frame straddling" approach, where the first image of the pair is acquired at the end of the first camera exposure, and the second image is acquired at the beginning of the second exposure.

The lasers were synchronized with the ICCD camera by an internal TTL signal generator and a trigger signal from the camera. In brief, if the camera frame corresponding to the first image in the pair starts at $t = 0$, the pulse with a width of 5 ns from the first laser is triggered just before the end of the first exposure at $t = 20\ \mu s$. The second camera frame corresponding to the second image in the pair starts at $t = 25\ \mu s$, and the 5 ns pulse from the second laser is triggered immediately after the start of the second exposure. Hence, the effective exposure time $\tau = 5$ ns, and the time interval within the image pair $\Delta t = 5\ \mu s$.

Although synchronizing the lasers and ICCD camera was straightforward, aligning the two laser beams so that they consistently illuminated the same region of the flow turned out to be more challenging, in part due to structural vibrations in the base plates of the DPSSL. The optomechanical setup for the pair of lasers was redesigned to enable independent adjustment of the two laser beams, but we were unable to implement this design before the end of the grant period.

SUMMARY OF RESULTS

The lead researcher on this project was Dr. Vladimir Tsiklashvili. Unfortunately, the project did not start until February 2015 due to major delays in the approval of his Optional Practical Training by the US Citizenship and Immigration Service. Figure 4 shows a representative double-exposure image of $a = 0.25\ \mu m$ particles illuminated by evanescent waves and convected by turbulent channel flow at $Re = 2.9\times10^4$ based on the channel hydraulic diameter $H = 1$ mm and average speed $\bar{V} = 1.75$ m/s. The two exposures on this single frame are separated by $\Delta t = 20\ \mu s$, and are obtained by pulsing a single DPSSL at 50 kHz. These images are obtained near the center of the channel to minimize the effect of the side walls. We strongly suspect that he nonuniformities in this image are due to: *a*) variations in the intensity of the evanescent-wave illumination; and *b*) local variations in tracer particle concentration in this high-shear flow.

At this point, most of the major technical problems have been resolved, despite the delay in starting this project, and we have demonstrated that this system can obtain images of particles in wall turbulence with a high enough SNR that they could, with minor improvements, be used to estimate the velocity components parallel to and within 1 μm of the wall. Although the STIR grant supporting this project ended at the end of May 2015, the project continued through mid-August, or for an additional 2.5 months, and Dr. Tsiklashvili is now working with Prof. Devesh Ranjan in the Woodruff School of Mechanical Engineering at Georgia Tech. We have clearly demonstrated that it is feasible to image particles illuminated by evanescent waves with a diameter well below a wall unit with high SNR over time scales that are comparable to those required to temporally resolve wall turbulence, albeit at low *Re*.

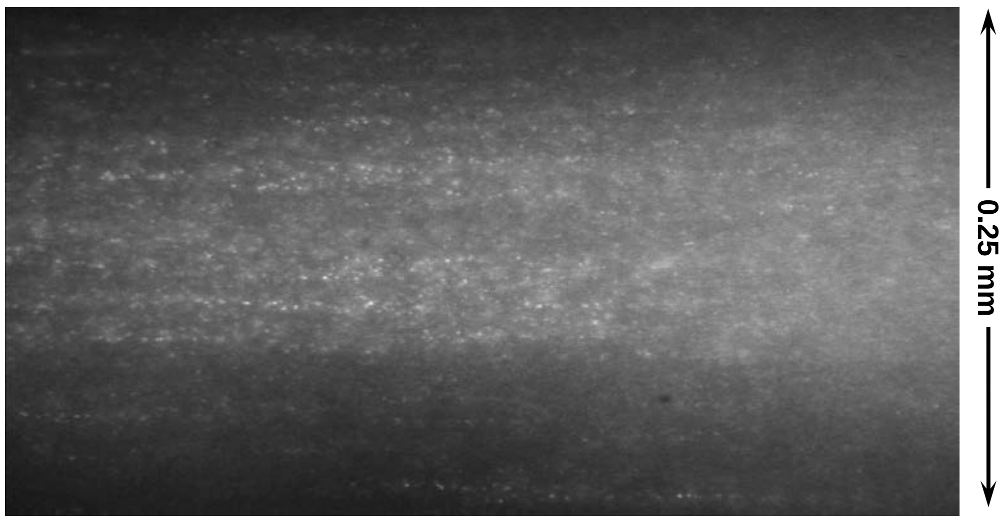

Figure 4 A "typical" double-exposure image of tracer particles in a turbulent channel flow illuminated by two pulses of evanescent-wave illumination with a width of 5 ns and a temporal spacing of 20 μs. The physical dimensions of the field of view are 0.45 mm × 0.25 mm. Flow goes from left to right in this image.

Although we lack the resources (especially personnel) at present to make further progress, the major tasks that remain in terms of obtaining PTV data in the viscous sublayer are:

- Improving the optical alignment of the two laser beams so that we can obtain pairs of (single-exposure) particle images separated by Δt = 5 μs so that each laser illuminates exactly the same location in the flow;
- Expand the laser beams to illuminate larger portion of the flow with less variation in illumination intensity and spatially filter the laser beams to minimize "leakage" of light transmitted into the flow (*vs.* totally internally reflected at the fluid-glass interface), since we suspect that much of the background noise evident in Figure 4 is due to a small amount of transmitted light
- Investigate locally seeding the boundary layer to provide more uniform seeding in the viscous sublayer, which could have the additional advantage of reducing background noise by reducing light scattered by particles in the bulk flow

We estimate that implementing these improvements require about 3 more months of full-time effort.